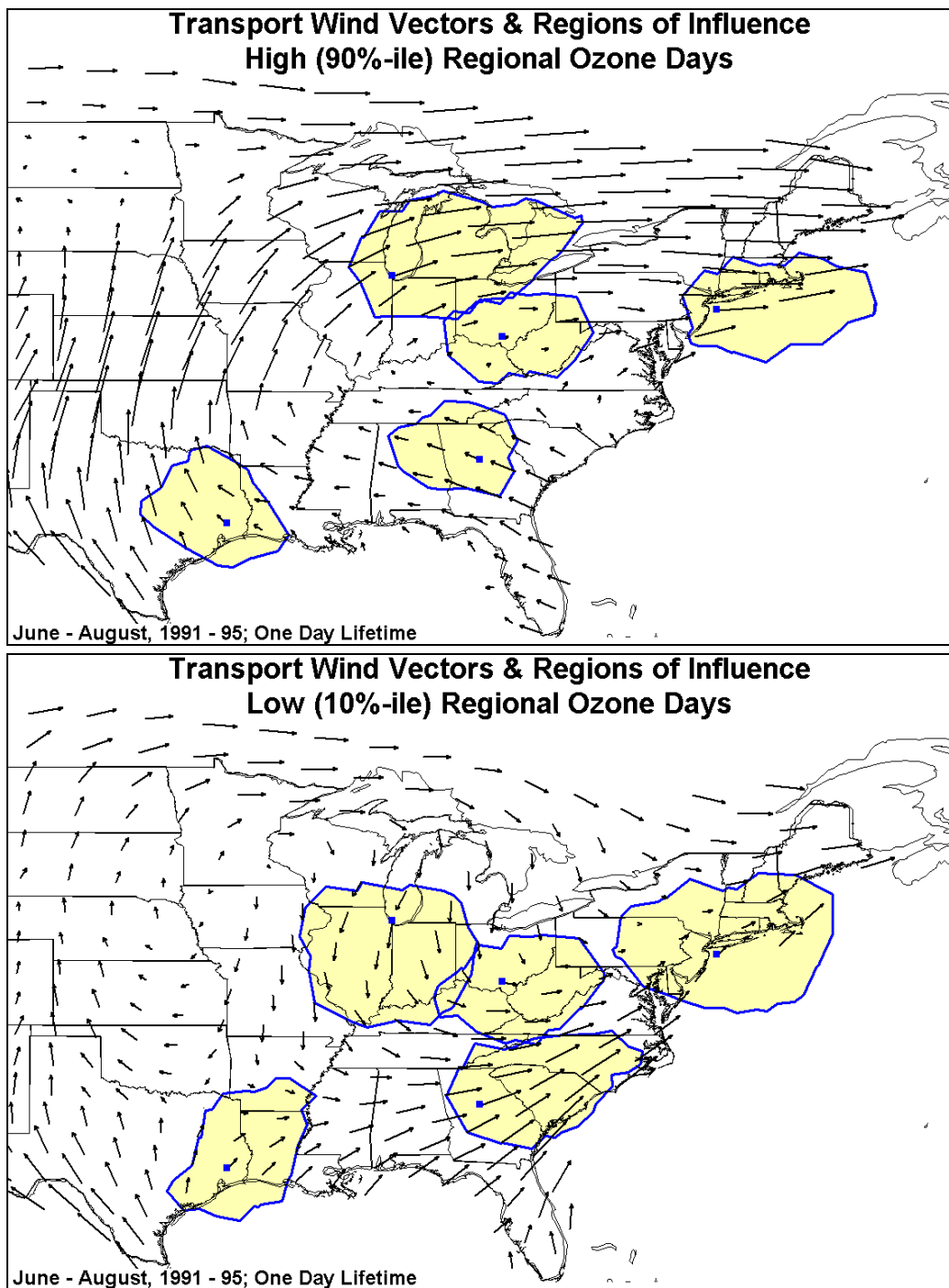


## **Transport During High and Low Ozone Days**

Ozone transport on days of regionally high and low ozone concentrations was also investigated in the analyses conducted for this report. Ozone transport, precursor emissions, and the influence of wind were examined in two ways. First, from the transport climatology, regions were identified where transport conditions are conducive to the accumulation of ozone from local or sub-regional sources, as well as where influence by regional scale transport can be seen. Second, by contrasting the transport conditions during periods of high and low ozone concentrations, unique transport pathways for a given region, as well as common pathways for multiple regions, were identified. The results of this analysis are summarised below and presented fully in a background paper (Schichtel and Husar, 1999).

Transport conditions were established for regionally high (90<sup>th</sup> percentile) and low (10<sup>th</sup> percentile) daily maximum 1-hour ozone concentrations. Figure 15 shows source regions of influence (SRI) overlaid with transport wind vectors. The wind vectors convey the direction and magnitude of the air mass transport while the SRIs represent the area encompassing the source impact and resultant air mass transport direction and speed. The SRIs are for the nearest modelled regions to Atlanta, Houston, Chicago, the Ohio River Valley, and New York City. At each source region, the highest and lowest daily maximum ozone values usually occurred on different days. Therefore, the transport conditions at each source region represent transport over different time periods.

Regionally high ozone days (Figure 15A) were associated with slow meandering or recirculating transport over Kentucky, Tennessee, and West Virginia, with strong clockwise transport around this region. It is clear that transport from sources in the southern Great Lakes border region moves from the United States into Canada, over the most dense emission regions of Southern Ontario, and back into New York and the New England States. This flow pattern is consistent with that of a large high-pressure system over eastern North America. The regionally low ozone days (Figure 15B) had northerly flow into Canada from Wisconsin and Michigan that converged over Kentucky and Tennessee with swift westerly-southwesterly flow in the Southeast. In New England, substantial transport occurred in all directions with resultant mass transport to the East.



**Figure 15. Transport wind vectors and source regions of influence for the highest (A) and lowest (B) 10% of regional ozone days during June – August, 1991 - 1995.** Transport vectors in Figure A, regionally high ozone days, show wind speed and directions consistent with regional-scale episode, i.e., strong clockwise transport. There is substantial transport into southern Ontario, particularly from the Chicago source region. Figure B, low regional ozone days, show transport vectors from the Great Plains into the Prairie provinces, east towards southern Ontario and south into the New England states. The New York source region shows substantial transport in all directions, while transport is primarily south in the Chicago source region.

## ***Air Quality Analysis Conclusions***

Ozone is not emitted directly, but produced in photochemical reactions involving NO<sub>x</sub> and VOC emissions. High ozone concentrations occur in and around many of the urban-industrialised areas in the transboundary region in both countries, resulting in frequent exceedences of current and proposed air quality objectives and standards. Elevated concentrations also occur over areas several hundred kilometres downwind of urban areas, causing exceedences of the objectives and standards in relatively less populated non-industrial areas. Some of these exceedences can occur at night as a result of ozone transport.

Transport of ozone and precursors has no boundaries. Polluted air masses can travel across states and provinces and between the United States and Canada. High ozone concentrations are typically located downwind of areas with the highest emissions. In the Canada-U.S. transboundary region, a more uniform pattern of ozone concentrations occurs across the region. The result is a regional “sea” of elevated ozone, extending east from the Mississippi River to the Atlantic coast and north-northeast into the Windsor-Québec City Corridor and New Brunswick and Nova Scotia, punctuated by “hot-spots” associated with dense emissions areas.

Emissions of NO<sub>x</sub> in the area were shown to form a boundary around the populated transboundary region, with dense emissions in the Windsor-Quebec corridor, and along the Atlantic coast from New Jersey to Massachusetts. The Ohio River Valley area, dense in precursor emissions, sits at the “entrance” of these twin transboundary emissions corridors.

Ozone transboundary flux data, presented in the section on wind speed and direction, illustrate flows in both directions, but are consistent with greater transport of ozone from the United States to Canada than from Canada to the United States. Concentrations along the Detroit-Windsor-Québec City corridor, and eastward, are increased when the wind blows from the “entrance” of the corridor, both towards the northeast, and north-northeast around the Great Lakes and out to the Atlantic.

Increasing wind speeds generally bring about reductions in locally produced ozone concentrations in urban areas. Ozone concentrations in the northeast urban corridor, along the Atlantic coast, are reduced when the ozone and precursor emissions are blown out to sea. For border areas where local concentrations remain constant with wind speed, it appears that the regional transport dominates ozone concentrations. This is observed in several of the urban areas along the border (e.g., Detroit, Windsor, and Toronto) where ozone concentrations were not reduced with increasing wind speeds.

Designing ozone control strategies is complicated because the effectiveness of strategies depends on factors such as meteorological conditions, the absolute and relative amounts of VOCs and NO<sub>x</sub>, the spatial and temporal distribution of anthropogenic and natural emissions, and background concentrations. The air quality data analysis section discussed the interrelationships between these factors and how each influences ozone concentrations. Some general conclusions can be made, therefore, regarding the effectiveness of strategies in the Canada-U.S. transborder region, based upon the conclusions from earlier reports and the information presented in this report. In the urban areas, a combination of VOC and NO<sub>x</sub> emission reductions are expected to lead to reductions in high ozone levels locally and downwind. In the areas affected by transport of ozone and precursor emissions, the downwind

urban, suburban and rural areas, i.e. the Canada-U.S. transborder region, NO<sub>x</sub> reductions are expected to be more effective.

The next section presents the results of air quality modelling using Canadian and U.S. data and forecasts of planned reduction program, focusing on NO<sub>x</sub> emission reductions to show the likely impact of emission control scenarios in the transboundary region.

### **3. AIR QUALITY MODELLING**

EPA and Environment Canada worked jointly to develop an expanded air quality modelling assessment for this report. The major purpose of this modelling was to evaluate the effectiveness of combined illustrative NO<sub>x</sub> control strategies in reducing regional ozone concentrations, with an emphasis on the transboundary region of concern. As discussed previously, this modelling focuses on NO<sub>x</sub> controls because NO<sub>x</sub> reductions are generally more effective in reducing ozone on a regional basis than VOC reductions. The modelling emphasis on the effectiveness of example NO<sub>x</sub> control strategies is not intended to constrain the range of control options to be discussed in any future negotiations on an ozone annex.

#### ***Model Setup and Episodes***

The modelling for the assessment of regional strategies consisted of model runs using the Variable Grid Urban Airshed Model (UAM-V). This model was chosen for several reasons. This model has been widely used and generally accepted for policy applications in the U.S. In addition, it was readily available to be adapted for the analyses done for this report. The inputs needed to run the model (e.g., emissions and meteorological data) have been developed for a domain that covers much of the portion of the Canada-U.S. border that is of primary interest. A wide range of stakeholders reviewed these inputs. The configuration of the model used for this report is the same as that used for OTAG. The OTAG final report (OTAG, 1997) describes this in detail and addresses model performance and other issues related to application of the model for purposes of evaluating regional transport.

Modelling was done using the OTAG modelling domain, which includes portions or all of 37 states and the District of Columbia and parts of three Canadian provinces: Ontario, Quebec, and New Brunswick. The domain, therefore, incorporates some but not all areas of concern in eastern Canada and in particular, leaves out the Southern Atlantic Region. Two episodes were selected for evaluation: July 1-11, 1988 and July 7-18, 1995. These episodes were chosen because they represent conditions that suggest interregional transport over the areas of interest.

#### **Emissions**

EPA developed emissions for the United States and Environment Canada provided emissions for the Canadian portion of the modelling domain. The U.S. base year emissions are the same as those used for the development of the final rulemaking for the NO<sub>x</sub> SIP Call. These emissions are based on continuous emissions monitoring data for utilities and OTAG emissions for other sources and have been revised to reflect comments received during the public comment period for the NO<sub>x</sub> SIP Call. The base emissions for Canada are taken from the official Canadian 1990 National Emissions Inventory developed and compiled by the federal and provincial/territorial governments.

#### **Scenarios Modelled**

Two scenarios were modelled: a projected 2007 base case and one control scenario. The base case scenario is intended to represent conditions in 2007 if no emissions reductions occur in either country beyond what is currently mandated. For the United States, the base

case includes growth to 2007 and the application of Clean Air Act mandated controls as well as certain Federal measures that have been or are expected to be promulgated. This base case is described in detail in the final rulemaking for the NO<sub>x</sub> SIP Call (EPA, 1998). For Canada, the base case includes growth to 2007 and the implementation of actual programs and measures that are described in detail in the National Air Issues Coordinating Committee (NAICC) Base Case Consensus Forecast (NAICC, 1996).

The control scenario was developed to represent potential additional NO<sub>x</sub> reductions. For the United States, this includes the effects of the NO<sub>x</sub> SIP Call as shown in Table 2 and described in detail in the final rulemaking for the NO<sub>x</sub> SIP Call.

**TABLE 2. CONTROLS ASSUMED FOR SOURCES IN THE UNITED STATES.**

Sources	Controls
Large Electricity Generating Units	0.15 lb NO <sub>x</sub> /mmBtu, implemented through a regional trading program
Large Industrial Boilers and Turbines	60% reduction from uncontrolled levels
Large Glass Manufacturing Facilities	30% reduction from uncontrolled levels
Large Internal Combustion Engines	90% reduction from uncontrolled levels

For large electricity generating units, 1995 or 1996 heat input was grown to 2007 and the 0.15 lb NO<sub>x</sub>/mmBtu limit was applied. For the other categories listed in the table, emissions were projected to 2007, any control efficiency that had been applied was removed, and the control efficiency listed above was applied. For all other sources the control case is the same as the base case.

Because the Canadian NO<sub>x</sub> reduction program is not yet completely defined, the Canadian control scenario was developed as a "what if" case. The control scenario began from the basis of a "25% across the board" emission reduction for the province of Ontario for all sectors for both NO<sub>x</sub> and VOC from 1990 by 2007. In terms of the Ontario government Smog Plan commitment to reduce NO<sub>x</sub> and VOC emissions by 45% from 1990 by 2015, an "across the board" 25% reduction by 2007 was considered an appropriate scenario to model. The application of the "25% across the board" premise resulted in emission reductions as shown in Table 3.

**TABLE 3. CONTROLS ASSUMED FOR SOURCES IN ONTARIO.**

Category	% NO <sub>x</sub> Reduction from 1990	% VOC Reduction from 1990
Power Generation	25%	0% (Base Case used)
Industrial Sources	25%	25%
Fuel Combustion	25%	3.5% (Base Case used)
Incineration/other	0% (Base Case used)	25%
Transportation	25%	29% (Base case used)

Wherever a reduction in the Table differs from 25%, the base case scenario reduction was used. The rationale for the use of the base case reduction was:

1) few emissions of that pollutant are produced making a 25% reduction unrealistic (as in the case of VOC emissions from power generation where the provincial total in 1990 was 0.4 kilotonnes);

2) the base case forecast reduction for 2007 is already greater than 25% (as in the case of the VOC emissions from the transportation sector); or

3) an assessment was made that technology to meet a reduction of 25% is not available (as in the case of a 25% reduction of VOC from the fuel combustion sector).

For the provinces of Quebec and New Brunswick, the same approach was used for the transportation sector as for the province of Ontario and with respect to the other sectors, the control case reductions were the same as the base case.

For the purpose of evaluating model results, the 2007 control case is compared to the 2007 base case. It is important to understand the difference in emissions between these two model runs in order to analyse properly the model results. The application of the controls described above translates to a 28% reduction in NO<sub>x</sub> emissions from the 2007 base case in the United States and a 12% reduction in NO<sub>x</sub> emissions and a 14% reduction in VOC emissions from the 2007 base case in Canada. These overall percent reductions are influenced by two factors. First, the reductions have been applied to some but not all sectors of the inventory in the United States and Canada. Second, in Canada, the control scenario reductions are applied to the 1990 emissions so that when the 2007 control case scenario emissions are compared with the 2007 base case emissions, the level of the reduction is offset by growth and abatement measures that are already incorporated in the base case scenario.

### **Analysis of Modelling Results**

The impacts of emission controls were evaluated by comparing the results of the base case run with the results of the control case run. Using the results in a comparative sense alleviates some of the concerns with uncertainties in absolute predictions. The 1-hour and 8-hour base case ozone predictions are shown in Figures 16 and 17, respectively. (These Figures and the ones that follow have been cropped so that they do not show the entire OTAG modelling domain but focus on the transboundary area of concern.) The change in the extent of values above the standards or objectives indicates the improvements in air quality due to the reduction in NO<sub>x</sub> emissions. This can be seen by looking at the difference in concentrations between the base case and control case. Figures 18 and 19 show the composite decrease in ozone concentrations throughout the area of interest. The decreases shown in these figures represent the maximum reduction in each grid over the two episodes modelled. These figures show that the controls assumed in the modelling runs result in a 2-10 ppb reduction in 1-hour and 8-hour ozone concentrations over nearly the entire area. For a large portion of the domain, particularly for the Ohio River Valley and surrounding areas in the United States, southern Ontario, and Sudbury, Canada, the reductions in 1-hour and 8-hour ozone concentrations are predicted to be greater than 14 ppb.

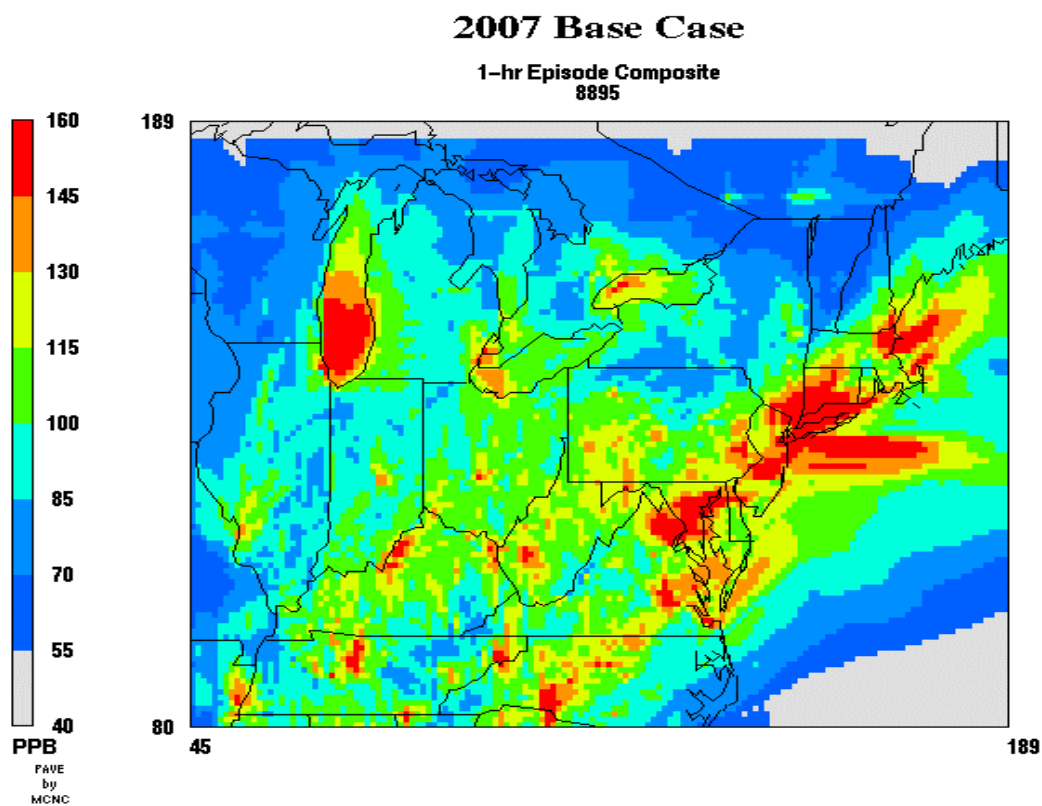


Figure 16. 2007 Base Case Episode Composite 1-hr Ozone Concentrations.

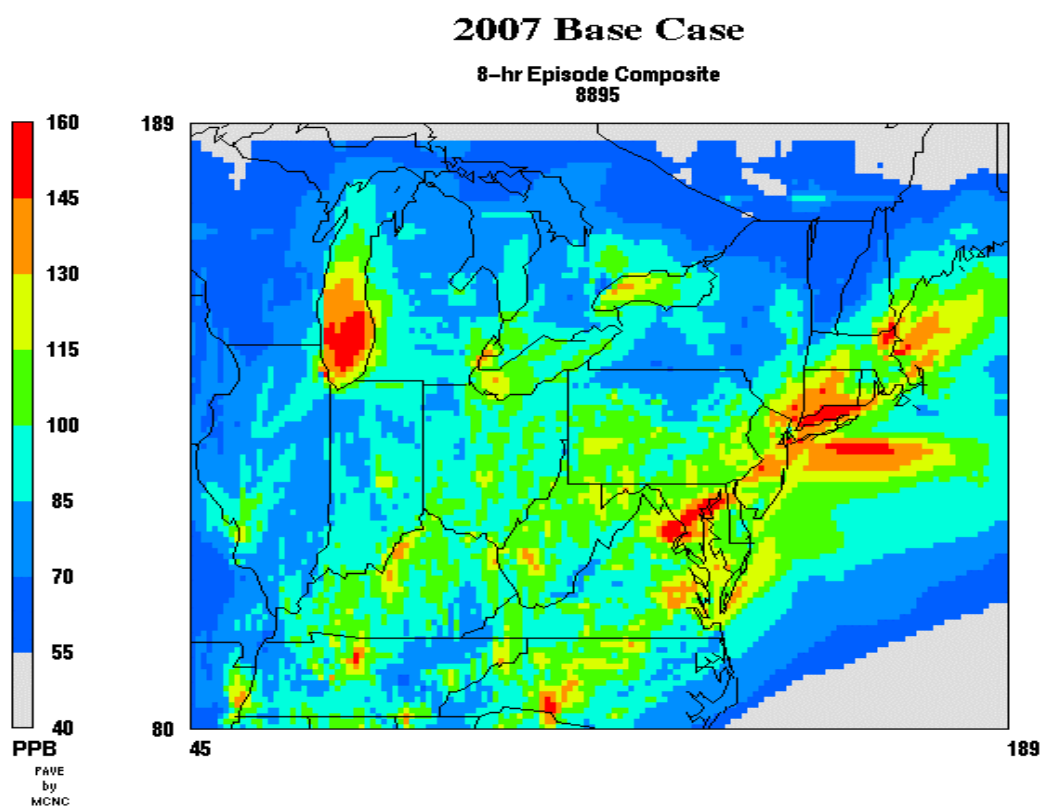
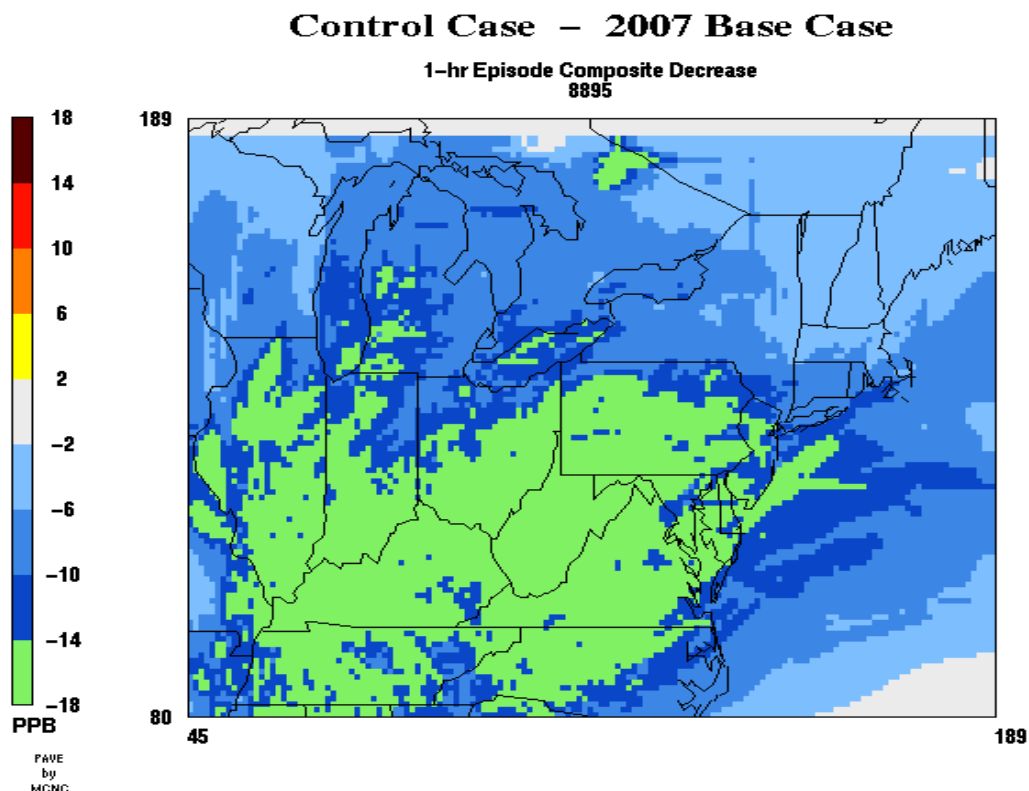
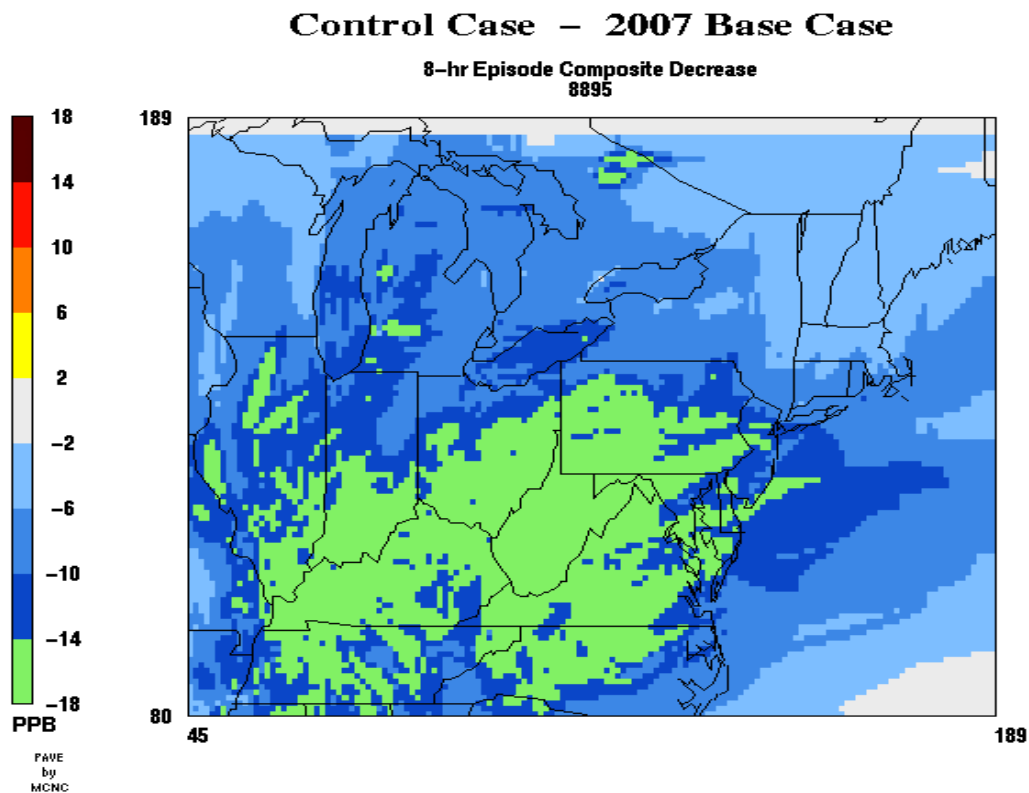


Figure 17. 2007 Base Case Episode Composite 8-hr Ozone Concentrations.



**Figure 18. Episode Composite Decrease in 1-hour Ozone Concentrations Between the Base Case and the Control Case.**



**Figure 19. Episode Composite Decreases in 8-hour Ozone Concentrations Between the Base Case and Control Case.**

In order to evaluate whether the reductions shown in Figures 18 and 19 are occurring in the areas of concern, the predicted maximum decreases that occur in areas that are above specified threshold levels in the base case were examined, along with predicted maximum increases in these areas. Figures 20 and 21 show these results for the thresholds considered. In these figures, the magnitude of decreases or increases is indicated using the colour scale shown at the left of each figure. The white areas on the maps indicate areas where the base case predicted ozone concentration is below the specified threshold. The grey areas indicate areas where the predicted base case ozone concentration is above the threshold, but there are no decreases or increases above 2 ppb. The thresholds chosen were 82 ppb for 1-hour values, which is the level of the current Canadian objective and 85 ppb for 8-hour values, which is the level of the current US 8-hour standard.

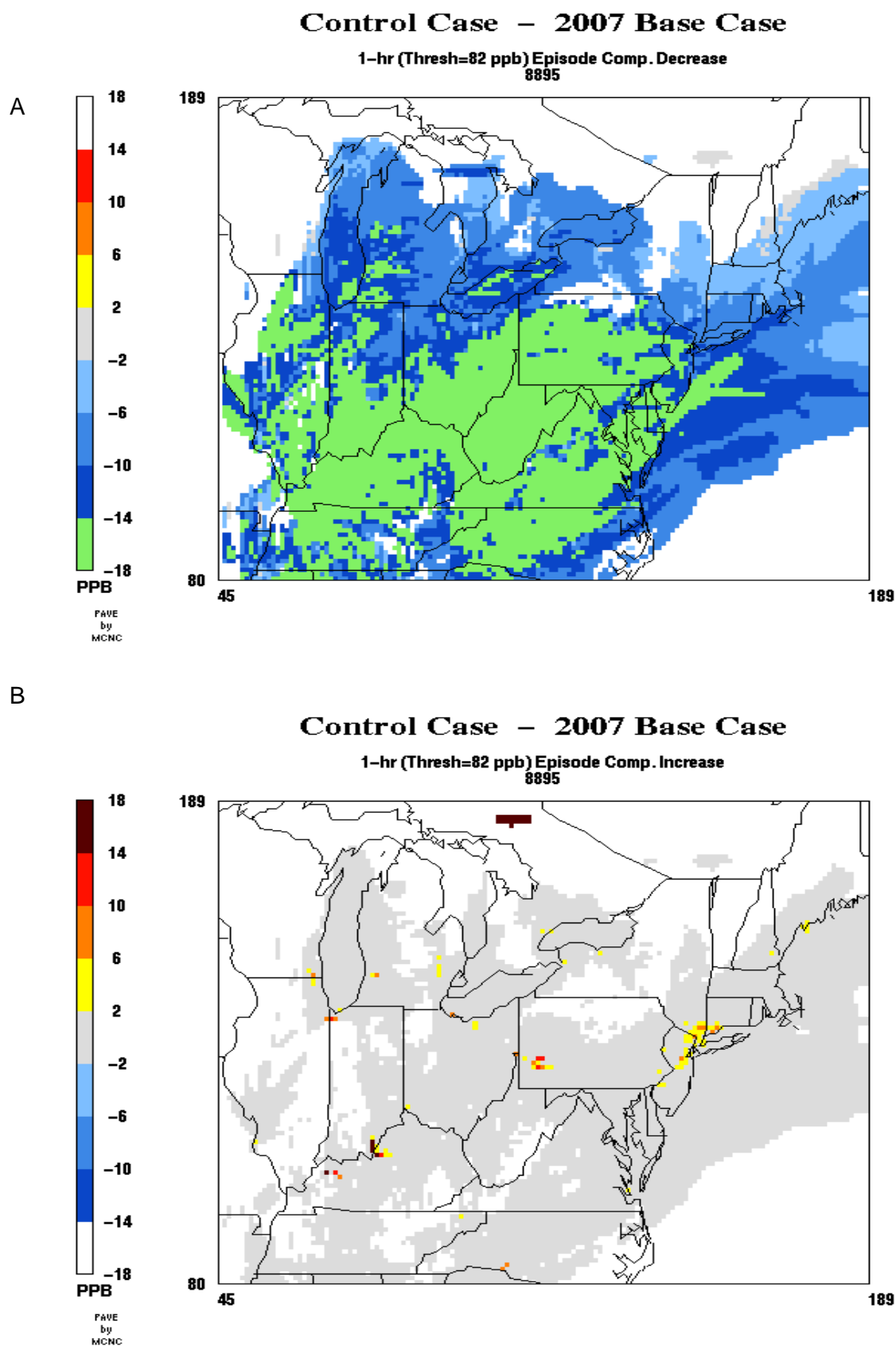
The results for the 1-hour 82 ppb and 8-hour 85 ppb thresholds are similar, although the geographic extent of reductions is somewhat smaller. Decreases are in the range of 10-14 ppb and higher in a broad area in both the United States and Canada. Increases are similar in magnitude and location in both cases.

## ***Air Quality Modelling Conclusions***

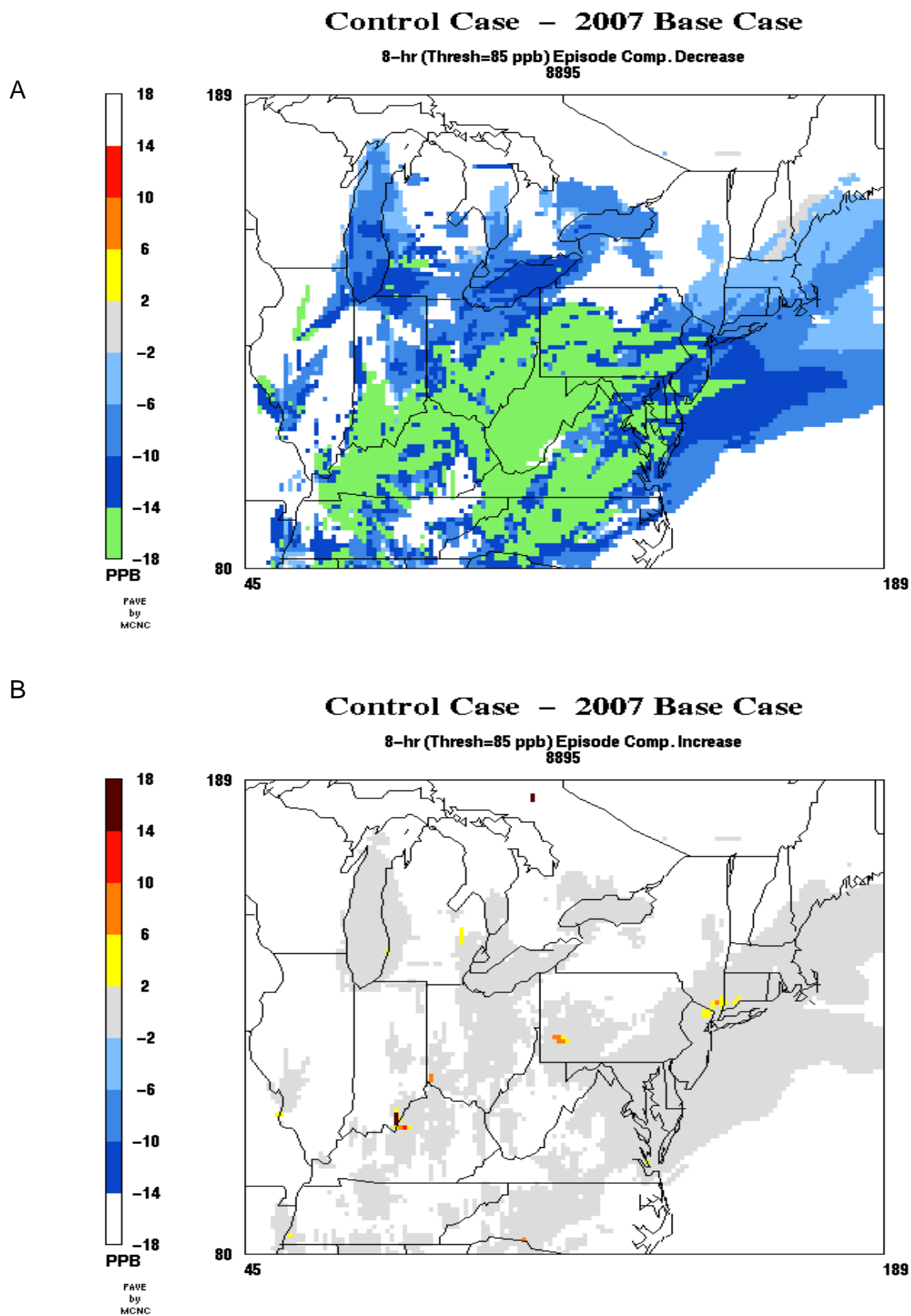
The results of the model runs show that there are substantial benefits to controlling NO<sub>x</sub> emissions in the United States and Canada. In the 2007 base case, without any additional controls, predicted ozone concentrations exceed the Canadian 1-hour objective and the U.S. 8-hour standard in a large portion of the modelling domain. The assumed reductions forecast for 2007 result in both 1- and 8-hour episode reductions of 6 to over 14 ppb ozone in a corridor from Michigan/western Ohio/southwestern Ontario to New York and eastern Ontario. Reductions of 2 to 6 ppb occur in New England states and Quebec. When the evaluation of the results is restricted to only those areas that are above specific thresholds in the base case, there are still benefits in the 6-14 ppb range and higher in many areas. The geographic extent of the benefits that are seen depends on the threshold that is chosen.

The benefits tend to be larger in the United States. This may be due, in part, to the fact that the emission reductions in the United States are larger both in term of percentage and total mass. The NO<sub>x</sub> SIP call strategy that was modelled for the United States results in a 28% reduction in NO<sub>x</sub> and the scenario modelled for Canada results in a 12% reduction in NO<sub>x</sub> and a 14% reduction in VOC. A control scenario in Canada that resulted in higher percentage reductions would increase the benefits that would be seen in Canada and the border region. Although the results also show predicted increases in some areas, they are more limited in geographic extent and are offset by the larger benefits. In fact, the benefits may be even greater than is indicated because of the limitation of the modelling domain with respect to Canada's Southern Atlantic Region and parts of the Windsor-Québec City Corridor.

In addition, there are other non-ozone benefits that can be expected from widespread NO<sub>x</sub> reductions. Decreases in NO<sub>x</sub> emissions will also decrease acid deposition, nitrates in drinking water, excessive nitrogen loadings to aquatic and terrestrial ecosystems, and ambient concentrations of nitrogen dioxide, particulate matter, and toxics.



**Figure 20. Predicted Maximum A) Decreases and B) Increases in 1-hr Ozone Concentrations in Areas  $\geq 82$  ppb in the Base Case.**



**Figure 21. Predicted Maximum A) Decreases and B) Increases in 8-hr Ozone Concentrations in Areas  $\geq 85$  ppb in the Base Case.**

#### **4. POLICY CONCLUSIONS RELEVANT TO THE CONSIDERATION OF AN OZONE ANNEX BY THE CANADA-U.S. AIR QUALITY COMMITTEE**

In eastern North America, ozone levels that exceed established and proposed norms often occur in large-scale regional episodes that do not respect political borders. Ozone is a reactive respiratory irritant and is associated with decreases in lung function, aggravation of respiratory disease, increases in hospital admissions and related health effects. Ozone also causes damage to forested ecosystems and agriculture. Furthermore, precursors that form ozone include substances that cause or contribute to acid rain and eutrophication of sensitive estuaries as well as toxic organic air pollutants.

This document presents results of cooperative efforts to analyse ozone transport in eastern North America. The approaches taken in the analyses represent an extension into the transboundary area of concern of analytical techniques, methodologies, and tools already being used in both countries to address domestic air pollution. They include integrated air quality data analyses of patterns and episodes, consideration of emissions patterns together with analyses of ozone as a function of changing meteorological conditions and transport climatology, and finally, joint modelling of regional scale ozone transport and responses to control scenarios.

These technical analyses clearly demonstrate the connections between emissions, transport, and ozone occurrence on both sides of the border. These results strongly support the common-sense conclusion that coordination of planning and execution of control strategies for ozone precursors (NO<sub>x</sub> and VOC) for all source categories would be more beneficial than individual initiatives.

The United States has made major steps forward in addressing air quality in general and ozone in particular in recent years. Significant progress has been made in implementing the provisions of the 1990 Clean Air Act Amendments with respect to ozone precursors. The U.S. Air Quality Standards for ozone and particulate matter in air have been revised and tightened. The Ozone Transport Assessment Group (OTAG) successfully completed intergovernmental negotiations on ozone transport among 37 states. Finally, EPA has finalised a rule concerning revisions to State Implementation Plans (SIPs) in 22 States and the District of Columbia to respond to ozone transport through reductions in NO<sub>x</sub> emissions by 2007. Further actions are planned with respect to fuel sulphur and vehicular emissions.

In Canada, there have been similar efforts on air quality and ozone. The first and second phases of the NO<sub>x</sub>/VOC management program are complete with substantial programs for major sources of NO<sub>x</sub> and VOC nationally and in key problem regions aimed at achieving the current Canadian air quality objective of 1-hour 82 ppb. The Phase 3 Federal Smog Plan is underway for both ozone and inhalable particles and the Ontario Smog Plan is being implemented to reduce provincial emissions of NO<sub>x</sub> and VOC by 45% from 1990 levels by 2015. New sulphur in gasoline regulations are being promulgated and action on vehicular emissions are planned. Finally, Canadian governments are now engaged in developing, for the first time, Canada-Wide Standards and implementation plans for ozone and particulate matter in air.

The air quality data analyses conducted for this report focused on determining the pattern of transport in the transboundary area of concern in the eastern United States and Canada. The

results indicate that long-range transport of ozone and its precursors significantly influences the magnitude and persistence of high ozone concentrations in eastern North America. Air masses from the United States contribute to high ozone concentrations in Ontario, Quebec, New Brunswick and Nova Scotia. When winds blow from Canada, the southern shores of Lake Erie and the eastern shores of Lake Ontario experience high ozone levels. Due to the relative amounts of emissions in each country and the prevailing winds during the summer ozone season, more ozone and precursors flow north-northeast from the United States into Canada than south-southeast from Canada into the United States.

The extended regional air quality modelling conducted for this report demonstrates the effectiveness of illustrative joint precursor emission reduction strategies on ozone concentrations in the United States and Canada. The modelling indicates that there are substantial transboundary regional benefits to controlling NO<sub>x</sub> emissions in the United States and Canada. The assumed reductions forecast for 2007 result in both 1- and 8-hour episode reductions of 6 to over 14 ppb ozone in a corridor from Michigan/western Ohio/southern Ontario to New York and eastern Ontario. Reductions of 2 to 6 ppb occur in New England states and Quebec. Although not part of the modelling domain, it can be expected that there would also be reductions in ozone concentrations in the Southern Atlantic Region of Canada. While these analyses did not attempt to examine reduced acid deposition, nutrient loadings, and particulate matter levels that would accompany such strategies, these corollary improvements would certainly add to the total benefits of these example strategies.

The spatial and temporal patterns exhibited in the analyses of empirical air quality and emissions data are qualitatively consistent with the results of the air quality modelling analyses. Taken together, these results offer clear evidence of the rationale for discussing an effective bi-national approach for management of ozone and its precursors in eastern North America.

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